

Fabrication of long-period fiber gratings by focused irradiation of infrared femtosecond laser pulses

Yuki Kondo, Kentaro Nouchi, and Tsuneo Mitsuyu

Hirao Active Glass Project, Keihanna-Plaza, Super-Lab 2F6, Seika, Kyoto 619-0237, Japan

Masaru Watanabe

Showa Electric Wire & Cable Company, Ltd., Minami-Hashimoto 4, Sagamihara, Kanagawa 229-1133, Japan

Peter G. Kazansky

Optoelectronics Research Centre, University of Southampton, Southampton SO17 1BJ, UK

Kazuyuki Hirao

Faculty of Engineering, Kyoto University, Sakyo, Kyoto 606-8501, Japan

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We have fabricated long-period fiber gratings by use of a novel technique using focused irradiation of infrared femtosecond laser pulses. We investigate the thermal stability of the fabricated fiber gratings. The values of the loss peak wavelength and the transmittance of the fiber gratings after heat treatment below 500 °C are the same as initial values before heat treatment. The fiber gratings that were fabricated by this technique have a high resistance to thermal decay. We propose that this technique will be useful for fabrication of fiber gratings with a superior aging characteristic. © 1999 Optical Society of America

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Fiber gratings whose grating period is approximately 100 to 1000 μm are called long-period fiber gratings¹ (LPFG's) and are often used as gain-flattening filters for Er-doped amplifiers.² Since a periodic refractive-index structure can be easily obtained by use of a photorefractive effect of Ge-doped glasses, most LPFG's have been fabricated in germanosilicate optical fibers by UV-light irradiation. Irradiation with UV light causes an increase of the refractive index of these fibers owing to formation of Ge-related glass defects. Therefore, the technique using UV light can be applied only to Ge-doped fibers that produce this photorefractive effect. However, LPFG's fabricated by UV-light irradiation have a problem with an aging stability because the index change relaxes even below 100 °C.³ Moreover, enhancing the photosensitivity of these fibers requires extra processes such as hydrogen loading at high pressure or doping of photosensitive ions.

We have found that focused irradiation of femtosecond laser pulses causes a permanent refractive-index increase in various glasses.^{4,5} In this Letter we report a novel technique for fabrication of LPFG's by focused irradiation of femtosecond laser pulses. We induce a periodic structure of the refractive index in the core of a single-mode fiber by use of light that is not absorbed by core and clad glasses and a polymer coated upon the clad. The thermal stability of the LPFG's is also reported.

The experimental setup for the fabrication technique is shown in Fig. 1. The optical fiber that was used in this experimental was a standard single-mode fiber for telecommunication (N.A., 0.11; mode field diameter, $9.3 \pm 0.5 \mu\text{m}$; clad diameter, $125 \pm 2 \mu\text{m}$; cutoff wavelength, $1260 \pm 40 \text{ nm}$). The core and the clad glasses were Ge-doped and pure-silica glass, respectively.

The laser pulses that were used to induce refractive-index changes were obtained from a regeneratively amplified $\text{Ti}^{3+}:\text{Al}_2\text{O}_3$ laser pumped by an Ar^+ laser. The pulse width was 120 fs, the wavelength was 800 nm, and the repetition rate was 200 kHz. The laser beam was guided into a microscope and focused by a 20 $\times$ objective (N.A., 0.46) into the core. The features produced during focused irradiation of femtosecond pulses were observed through a CCD camera mounted upon the microscope. The fiber, which was fixed on a computer-controlled XYZ stage, was irradiated point by point. An optical spectrum analyzer simultaneously monitored the transmission spectra of the LPFG's that were being fabricated. The laser power was set at 150 mW by use of a neutral-density filter. The beam size before the objective was 6 mm, and the irradiation time was 10 s for each

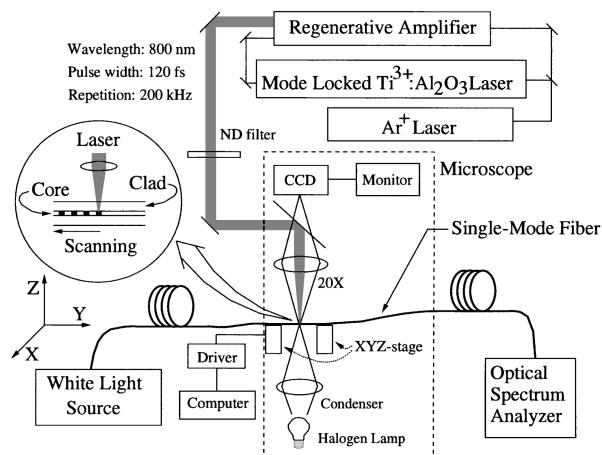


Fig. 1. Experimental setup for LPFG fabrication technique. ND, neutral density.

spot. Assuming that the femtosecond laser beam has a Gaussian profile, the spot size at the focal point and the Rayleigh length were estimated to be 2 and 3 μm , respectively. The fluence per pulse was 24 J/cm², and each spot was subjected to a dose of 50 MJ/cm² of energy. Since the total exposure dose was almost the same as in our previous study (100 MJ/cm²),⁴ the value of the index increase can be estimated to be the same value as that of the previous study (0.01).

At first, we tried to irradiate the fiber with femtosecond pulses without removing the polymer (acrylic resin) that was coated upon the clad. Although the laser power was weakened to such a degree that index change in the core did not occur, the resin was ablated.

We then irradiated the fiber with femtosecond pulses after removing the coated resin. Figure 2 shows the transmission spectrum of the 29.9-mm LPFG with a grating period of 460 μm . The resolution of the measurement is 1 nm. Large loss peaks whose FWHM are approximately 10 to 20 nm can be clearly observed. The appearance of these peaks owing to couplings from the guided mode to the forward-propagating clad modes¹ indicates that we have demonstrated a novel fabrication technique for LPFG's by focused irradiation of femtosecond laser pulses. Many small peaks can also be observed, and the transmission spectral shape is complicated. We confirmed that focused irradiation induces an index increase in the clad as well as in the core. Unless laser pulses are focused only in the core, the index of the clad also changes. During fabrication of LPFG's, deviation of the core position from the focal point along the x or the z axis in Fig. 1 results in an index increase of the clad and in point-by-point irregularity of the index-change region. The irradiation technique has not yet been perfected to induce regular index modulation in the fiber. The complexity of the spectral shape can be attributed to the irregularity of the index modulation. The excess loss value is more than 4 dB, which is remarkably large compared with that of LPFG's fabricated by UV-light irradiation (0.2 dB). The excess loss decreases with an increase in wavelength and has a maximum near the cutoff wavelength (1260 $\pm$ 40 nm). The large excess loss may be caused by scattering owing to some type of damage formed within the core and the clad and by overlap of the loss peaks owing to irregular refractive-index modulation. In addition, considering that the excess loss has a maximum near the cutoff wavelength, some radiation mode may be generated. To improve the spectral complexity of the fiber and reduce the large excess loss, regular index modulation in the fiber is necessary.

To investigate the thermal decay of the LPFG fabricated by the new technique, we measured its transmission spectrum after continuous heating at various temperatures for 480 min and subsequent cooling to 20 $^{\circ}\text{C}$. Figure 3 shows the loss peak wavelength, λ_p , at 1.49 μm in Fig. 2 and the transmittance, T_p , at λ_p . We find that from 20 to 500 $^{\circ}\text{C}$, both λ_p and T_p recover to their initial values before heat treatment, within errors. This result indicates that the LPFG's have high resistance to thermal decay below 500 $^{\circ}\text{C}$, which shows that they have a superior aging charac-

teristic. Since thermal degradation of fiber Bragg gratings fabricated by UV-light irradiation occurs even at temperatures below 100 $^{\circ}\text{C}$,³ annealing of the grating at an elevated temperature for a short time, thereby removing the unstable part of the UV-induced index, is required for thermal stability of grating performance.⁶ On the other hand, LPFG's fabricated by focused irradiation of femtosecond pulses have high resistance to thermal decay despite having no special stabilization. This thermal stability can be achieved because the cause of the index increase induced by focused irradiation of femtosecond pulses is different from that of the UV-induced index increase. In the case of UV-induced gratings in Ge-doped silica glass, photoexcitation of oxygen-vacancy-defect states forms paramagnetic GeE' centers that contribute to the index change.⁷ Because the defects related to GeE' centers relax even at temperatures below 100 $^{\circ}\text{C}$, the grating performance degrades thermally. Variations of λ_p and T_p after heat treatment above 500 $^{\circ}\text{C}$ indicate that the index change induced here relaxes above 500 $^{\circ}\text{C}$. Therefore, it seems that the index increase induced by focused irradiation of femtosecond pulses cannot be attributed to Ge-related defects and that different factors may account for it. From observation with an atomic-force microscope a local densification in glass irradiated by focused irradiation of femtosecond pulses at 800 nm was previously found.⁵ In addition, a nonlinear reaction through a multiphoton process and (or) conventional heating by a multiphoton transition can occur during laser irradiation. Varying the laser fluence revealed that the photoreaction that induced the index change had a threshold in fluence,

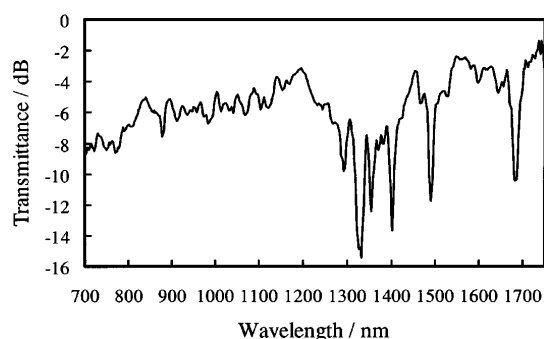


Fig. 2. Transmission spectrum of a 29.9-mm LPFG with a grating period of 460 μm .

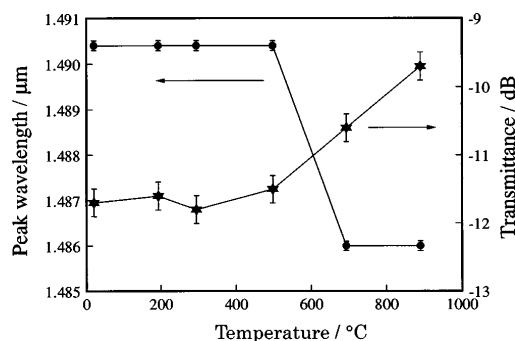


Fig. 3. Variations of the loss peak wavelength and the transmittance of the LPFG after heat treatment.

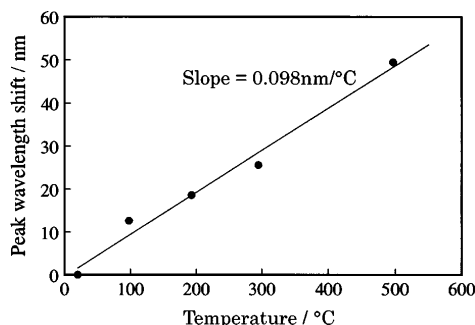


Fig. 4. Shift of the loss peak wavelength of the LPFG with temperature.

and a void was formed when the fluence was high enough. The fluence dependence on the value of the index change was complicated. According to Glezer and Mazur,⁸ a void is formed in a focal area surrounded by densified material, owing to energy transfer from a hot, high-density electron plasma created by a femtosecond laser pulse sent into the lattice. It is reasonable to expect that the index change that was observed in this study occurred because of a similar thermal effect. At a fluence lower than the level at which a void cannot be created, an index increase probably results from densification of a focal point owing to local melting and rapid quenching by laser irradiation. It should be noted that densification has also been observed in the case of UV irradiation. It is known that an increase in the refractive index of SiO₂ glass densified by application of high pressure through heating is stable at temperatures less than those initially applied.⁹ Since densification by focused irradiation of femtosecond pulses might result from some thermal effect, it shows high thermal stability, whereas densification by UV-light irradiation results from structural change that is due to electron transfer from Ge-related defects, which hardly accompany a thermal process. Further study is needed to clarify the mechanism of the index change induced by focused irradiation of femtosecond pulses.

We also studied the thermal shift of λ_p by heating the LPFG from 20 to 500 °C. Figure 4 shows the shift of λ_p at 1.49 μm in Fig. 2 with the temperature of the LPFG. The shift of λ_p is proportional to the increase in temperature from 20 to 500 °C, and the temperature dependence of λ_p ($d\lambda_p/dT$) is 0.098 nm/°C. This value is almost the same as the values of LPFG's fabricated by UV-light irradiation in standard telecommunication-grade fibers (0.05–0.15 nm/°C).¹⁰ The fact that the shift of λ_p is proportional to the increase in temperature from 20 to 500 °C indicates that the LPFG's fabricated by focused irradiation of femtosecond pulses can operate sufficiently as high-temperature sensors at up to 500 °C.

Long-period fiber gratings operate on the principle of phase matching between two modes in a fiber, with the peak wavelength λ_p of coupling being given by¹

$$\lambda_p = (n_{01} - n_{lm})\Lambda, \quad (1)$$

where Λ is the grating period and n_{01} and n_{lm} are

the effective indices of the LP₀₁ and LP_{lm} modes, respectively. Then, the temperature dependence of the peak wavelength, $d\lambda_p/dT$, is given by differentiation of Eq. (1):

$$\frac{d\lambda_p}{dT} = \frac{d\Lambda}{dT} \Delta n + \Lambda \frac{d\Delta n}{dT}, \quad (2)$$

where Δn is the difference in the effective indices ($\Delta n = n_{01} - n_{lm}$). The temperature dependence of the grating period, $d\Lambda/dT$, and the difference in the effective indices (Δn), $d\Delta n/dT$, result from the thermal-expansion coefficient α and the temperature dependence of the refractive index of the glass, respectively. In this experiment the glass composition of the core was Ge-doped silica. It was previously found that focused irradiation of femtosecond pulses induced increases in the refractive indices of various glasses.^{4,5} Therefore, if one selects glass composition by considering a thermal-expansion coefficient and the temperature dependence of the refractive index, it seems that focused irradiation of femtosecond laser pulses is capable of controlling any value of $d\lambda_p/dT$ as desired.

In conclusion, we have demonstrated a novel fabrication technique for LPFG's by focused irradiation of infrared femtosecond laser pulses. It has also been shown that LPFG's have a proportional dependence of loss peak wavelength on temperature from 20 to 500 °C and exhibit no degradation of grating performance. Compared with LPFG's fabricated by UV-light irradiation, those fabricated by focused irradiation of femtosecond pulses have high temperature resistance and a superior aging characteristic.

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